



## **FORMING STRUCTURES THAT INCLUDE A RELAXED OR PSEUDO-RELAXED LAYER ON A SUBSTRATE**

### **CROSS-REFERENCE TO RELATED APPLICATIONS**

- 5           This application claims the benefit of provisional application 60/483,476 filed June 26, 2003.

### **BACKGROUND ART**

- 10           The present invention generally relates to the formation of a relaxed or pseudo-relaxed layer on a substrate. The relaxed layer may be made of a material selected from semiconductor materials, in order to form a final structure for electronics, optics or optoelectronics, such as a semiconductor-on-insulator structure.

- 15           A layer is "relaxed" if its crystalline material has a lattice parameter substantially identical to its nominal lattice parameter, wherein the lattice parameter of the material is in its bulk equilibrium form. Conversely, a layer is "strained" if its crystalline material is elastically stressed in tension or in compression during crystal growth, such as during epitaxy, which forces its lattice parameter to be substantially different from its nominal  
20   lattice parameter.

- Methods for forming a relaxed layer on a substrate are known. A method for doing so includes conducting epitaxial growth of a thin layer of semiconductor material on a donor substrate, bonding a receiver  
25   substrate at the thin layer; and then removing a part of the donor substrate. A semiconductor-on-insulator structure can thus be made. The semiconductive thickness consists partially of the relaxed thin layer, and the insulating layer is usually formed in an intermediate step between the epitaxial and bonding steps.

- The thin layer may be fabricated during an epitaxial step or during  
30   subsequent treatment. In the first case, it is known to use a donor substrate consisting of a backing substrate and a buffer layer, the buffer

layer confining plastic deformations so that the epitaxial thin layer is relaxed from any stress. Such methods are, for example, described in published documents US 2002/0072130 and WO 99/53539. However, a buffer layer is often time consuming and costly to make. In the second case, the donor substrate does not comprise any buffer layer and the epitaxial step then consists of growing the thin layer to be stressed by the donor substrate. Thus, for example, a SiGe layer will be grown directly on a Si substrate that has a thickness such that the SiGe layer is globally stressed.

10 A first technique for relaxing the SiGe layer, notably as described in the document of B. Höllander et al. entitled "Strain relaxation of pseudomorphic  $\text{Si}_{1-x}\text{Ge}_x/\text{Si}(100)$  heterostructures after hydrogen or helium ion implantation for virtual substrate fabrication" (in Nuclear and Instruments and Methods in Physics Research B 175-177 (2001) 357-  
15 367) consists of relaxing the SiGe layer, before applying a bonding step, by implanting hydrogen or helium ions in the Si substrate at a predetermined depth. However, relaxation rates usually obtained with this first technique remain rather low as compared with other techniques.

A second technique is disclosed in the document entitled  
20 "Compliant Substrates: A comparative study of the relaxation mechanisms of strained films bonded to high and low viscosity" by Hobart et al. (Journal of Electronic Materials, vol.29, No.7, 2000). After removing the donor substrate during a removal step, heat treatment is applied for relaxing or pseudo-relaxing a layer of stressed SiGe, bonded to a BPSG  
25 glass during the bonding step. During the heat treatment, the stressed layer thus seems to relax via the layer of glass which has become viscous due to the treatment's temperature. However, this latter technique involves relaxation of the SiGe thin layer when the latter is exposed. Exposure of such a SiGe layer (exposed) to a gas atmosphere during heat  
30 treatment (such as a room RTA treatment, a sacrificial oxidization, or a

recovery anneal) may prove to be disastrous for the quality of this layer, wherein Ge contained in the layer may diffuse outwards (which may cause decomposition of the layer) and the layer may be contaminated by external contaminants.

5           Furthermore, such a SiGe layer is on the surface and may therefore have to undergo special treatment such as finishing treatments (polishing, smoothening, oxidization, cleanings, etc.). At the present, such treatments for SiGe are not as effective as those for Si. This lack of control when working with SiGe causes further difficulties for making a  
10       desired structure.

          The present invention now overcomes these problems.

#### SUMMARY OF THE INVENTION

          The invention relates to methods of forming a relaxed or pseudo-  
15       relaxed layer on a substrate, wherein the relaxed layer is preferably of a semiconductor material. An implementation of the method includes growing an elastically stressed layer of semiconductor material on a donor substrate; forming a glassy layer of a viscous material to the stressed layer; removing a portion of the donor substrate to form a structure that  
20       includes the glassy layer, the stressed layer and a surface layer; and heat treating the structure at a temperature of at least a viscosity temperature of the glassy layer to relax the stressed layer.

          The glassy layer may be a semiconductor material layer that is grown on the stressed layer. Also, the glassy layer can be formed on a  
25       receiving substrate so that the structure includes the receiving substrate bonded to the glassy layer.

          The method also includes completing a controlled treatment that transforms at least a portion of the material layer into a viscous material at a viscosity temperature. The glassy layer could be formed on at least one

of the stressed semiconductor material layer of the donor substrate or on the receiving substrate prior to bonding to the stressed layer.

The method may also include using a controlled treatment that includes a second viscosity temperature to transform at least a portion of the surface layer into a second glassy layer, and the heat treating step can occur during or after the formation of the second glassy layer. The glassy layer and/or the second glassy layer may be formed by growing a Si material layer on the stressed layer, and completing a controlled thermal oxidization treatment for transforming at least a portion of the Si material layer into  $\text{SiO}_2$ , to form a  $\text{SiO}_2$  glassy layer. When desired, the method may further advantageously include removing the second glassy layer.

Implementations also relate to structures obtained after utilizing the method of forming a relaxed or pseudo-relaxed layer on a substrate. An embodiment of such a structure includes a substrate, a first glassy layer on top of the substrate, a semiconductor layer on top of the first glassy layer, and a second glassy layer on top of the semiconductor layer, wherein the semiconductor layer, after transfer to a receiving substrate, forms a buried layer thereon. Another structure includes a layer of a semiconductor material having a top surface; a first glassy layer on the top surface of the substrate; a semiconductor layer on the first glassy layer; a second glassy layer on the semiconductor layer; and a receiving substrate, wherein the second glassy layer forms a buried layer on the receiving substrate. Yet another structure includes a receiving substrate having a top surface; a glassy layer on the top surface of the receiving substrate; and a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer on the glassy layer. Additional layers may be provided on the relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer, such as another glassy layer, if desired.

The buried layer of the structure may be elastically stressed, or may be relaxed or pseudo-relaxed, and may be made of a  $\text{Si}_{1-x}\text{Ge}_x$

material. Another semiconductor layer may be interposed between the buried layer and the second glassy layer, or may be interposed between the first glassy layer and the buried layer. Further, at least one of the first and second glassy layers may be made of a SiO<sub>2</sub> material.

5        A layer of Si stressed by a relaxed or pseudo-relaxed SiGe layer is useful for providing desirable properties in these structures, such as a charge carrier mobility of the order of 100%, larger than that present within a relaxed Si layer.

#### BRIEF DESCRIPTION OF THE DRAWINGS

10        Other aspects, objects and advantages of the present invention will become more apparent upon reading the following detailed description of the preferred methods thereof, given as non-limiting examples, and made with reference to the appended drawings wherein:

15        Figures 1a-1i illustrate the different steps of a first method according to the invention.

Figures 2a-2i illustrate the different steps of a second method according to the invention.

Figures 3a-3i illustrate the different steps of a third method according to the invention.

20        Figures 4a-4i illustrate the different steps of a fourth method according to the invention.

Figures 5a-5i illustrate the different steps of a fifth method according to the invention.

25        Figures 6a-6i illustrate the different steps of a sixth method according to the invention.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

30        The present method overcomes the difficulties evident in the prior art by providing, according to a first aspect, a method of forming a relaxed or pseudo-relaxed layer on a substrate. The relaxed layer is a

semiconductor material. The method includes growing an elastically stressed semiconductor layer on a donor substrate, and forming, on the stressed layer or on a receiving substrate, a glassy layer consisting of a viscous material that has an associated viscosity temperature. The technique further includes bonding the receiving substrate to the stressed layer via the glassy layer, removing a portion of the donor substrate so as to form a structure that includes the receiving substrate, the glassy layer, the stressed layer, and the unremoved portion of the donor substrate which forms a surface layer. Lastly, the structure is heat treated at a temperature close to or higher than the viscosity temperature.

Other features of the method for forming a relaxed or pseudo-relaxed layer on a substrate include applying a controlled treatment after removing the portion of the donor substrate. The controlled treatment transforms at least a portion of the surface layer into a viscous material to form a second glassy layer having an associated second viscosity temperature. Further, the method may include heat treating the structure while forming or after forming the second glassy layer. The second glassy layer may thereafter be removed. A crystal growing step can also be advantageously applied to the structure, using a selected semiconductor material.

The technique can also include forming a glassy layer by growing a semiconductor layer on the stressed layer, and performing a controlled treatment in order to transform at least a portion of the layer into a viscous material having a particular viscosity temperature. The glassy layer can be electrically insulating and the structure can be a semiconductor-on-insulator structure, the semiconductive thickness of which includes the stressed layer which has been relaxed or pseudo-relaxed during the heating step.

According to a second aspect, the method provides a structure for forming a relaxed or pseudo-relaxed layer on a substrate. The structure

includes a substrate, a first glassy layer, a buried layer of material selected from semiconductor materials, and a second glassy layer.

The present invention therefore pertains to forming a relaxed or pseudo-relaxed useful layer on a substrate. It also pertains to forming on  
5 the relaxed or pseudo-relaxed layer, a useful layer of stressed material. A "useful layer" is a layer intended to receive components for electronics, optics, or optoelectronics during subsequent treatments.

The present method also protects the layer to be relaxed or pseudo-relaxed from the atmosphere surrounding the structure in which it  
10 is contained, throughout the application of the method and especially during heat treatments. Such operation prevents at least one of the atomic species of the material from being able to diffuse.

The present method also permits application of different surface finishing techniques onto the desired structure during fabrication without  
15 damaging the quality of the layer to be relaxed or pseudo-relaxed. This can notably be achieved in the particular case when the layer to be relaxed or pseudo-relaxed is  $\text{Si}_{1-x}\text{Ge}_x$ , and when the use of different processing techniques on the structure, usually applied on Si structures or layers, is desired.

20 An implementation of the method is described with reference to Figures 1a to 1i. Figure 1a shows a source wafer 10 that consists of a donor substrate 1 and a stressed  $\text{Si}_{1-x}\text{Ge}_x$  layer 2. In a first configuration, the donor substrate 1 consists entirely of monocrystalline Si with a first lattice parameter. Advantageously, the donor substrate 1 is made by  
25 Czochralski growth. In a second configuration, the donor substrate 1 is a pseudo-substrate comprising an upper Si layer (not illustrated in Figure 1), exhibiting an interface with the stressed layer 2 and having a first lattice parameter at its interface with the stressed layer 2. Advantageously, the first lattice parameter of the upper layer is the nominal lattice parameter of  
30 Si, so that the latter is in a relaxed state. The upper layer further has a

sufficiently large thickness so as to be able to impose its lattice parameter to the overlying stressed layer 2, without the latter substantially influencing the crystalline structure of the upper layer of the donor substrate 1.

5        Whichever configuration is selected, the donor substrate 1 has a crystalline structure with a low density of structural defects, such as dislocations. Preferably, the stressed layer 2 only consists of a single thickness of  $\text{Si}_{1-x}\text{Ge}_x$ . The Ge concentration in this stressed layer 2 is preferably higher than 10%, i.e. an x value greater than 0.10. As Ge has a larger lattice parameter than Si by about 4.2%, the selected material for  
10        forming this stressed layer 2 thus has a second nominal lattice parameter which is substantially larger than the first lattice parameter. The formed stressed layer 2 is then elastically stressed in compression by the donor substrate 1, i.e. it is stressed so as to have a lattice parameter substantially less than the second lattice parameter of the material of  
15        which it is made, and therefore has a lattice parameter close to the first lattice parameter. Preferably, the stressed layer 2 further has a substantially constant composition of atomic elements.

Advantageously, the stressed layer 2 may be formed on the donor substrate 1 by crystal growth, such as by epitaxy by using known  
20        techniques such as for example, LPD, CVD and MBE (respective abbreviations of Liquid Phase Deposition, Chemical Vapor Deposition, and Molecular Beam Epitaxy) techniques. In order to obtain such a stressed layer 2, without too many crystallographic defects, such as for example point defects or extended defects such as dislocations, it is  
25        advantageous to select the crystalline materials forming the donor substrate 1 and the stressed layer (in the vicinity of its interface with the backing substrate 1) so that they have a sufficiently small difference between their first and their second respective nominal lattice parameters. For example, this lattice parameter difference is typically between about  
30        0.5% and about 1.5%, but may also have larger values. For example,  $\text{Si}_{1-x}\text{Ge}_x$ .



$x\text{Ge}_x$  with  $x=0.3$  has a nominal lattice parameter larger than Si by about 1.15%.

However, it is preferable that the stressed layer 2 have a substantially constant thickness, so that it has substantially constant intrinsic properties and/or facilitates the future bonding with a receiver substrate (as illustrated in Figure 1i).

In order to prevent relaxation of the stressed layer 2, or occurrence of internal plastic type deformations, the thickness of the latter should further be less than a critical thickness for elastic stress. This critical elastic stress thickness depends mainly on the material selected for the stress layer 2 and on the lattice parameter difference with the donor substrate. But it also depends on growth parameters such as the temperature at which it has been formed, on nucleation sites formed during epitaxial growth, or on the growth techniques used (for example CVD or MBE).

Examples of critical thickness values for  $\text{Si}_{1-x}\text{Ge}_x$  layers can be found by reference to the document entitled "High-mobility Si and Ge structures" by Friedrich Schaffler ("Semiconductor Science Technology" 12 (1997) 1515-1549). Concerning other materials, one skilled in the art can easily refer to state of the art publications in order to determine the value of the critical elastic stress thickness of a selected material for the stressed layer 2 formed on the donor substrate 1. Thus, a  $\text{Si}_{1-x}\text{Ge}_x$  layer with  $x$  between 0.10 and 0.30 has a typical thickness between 200 Å and 2,000 Å, preferably between 200 Å and 500 Å by notably adapting the growth parameters. Once formed, the stressed layer 2 therefore has a lattice parameter substantially close to that of its growth substrate 1 and exhibits internal elastic stresses in compression.

With reference to Figure 1c, a glassy layer 4 is formed on the stressed layer 2 according to a first embodiment. The material making up the glassy layer 4 becomes viscous when a viscosity temperature  $T_G$  is

reached. Advantageously, the material of the glassy layer 4 may be of one of the following materials: BPSG,  $\text{SiO}_2$ ,  $\text{SiON}$ . When a  $\text{SiO}_x\text{N}_y$  glassy layer 4 is formed, the value of  $y$  may advantageously be varied in order to change the viscosity temperature  $T_G$  which is substantially a function of the nitrogen composition for this material. Thus, by growing a composition thereon, it is now possible to change the  $T_G$  of the glassy layer 4 typically between a  $T_G$  of the order of that of  $\text{SiO}_2$  (which may vary around  $1,150^\circ\text{C}$ ) and a  $T_G$  of the order of that of  $\text{Si}_3\text{N}_4$  (which is higher than  $1,500^\circ\text{C}$ ). A large  $T_G$  range may thereby be covered by varying  $y$ . The  $T_G$  values of the glassy layer 4, if they essentially depend on the material of the glassy layer, may also fluctuate according to the conditions under which the glassy layer was formed. In an advantageous scenario, the conditions for forming the glassy layer 4 may thereby be adapted in a controlled manner in order to select a  $T_G$  "à la carte". Deposition parameters such as temperature, duration, dosage and potential of the gas atmosphere, and the like, may thus be varied. Further, doping elements may be added to the main gaseous elements contained in the vitreous atmosphere, such as boron and phosphorus which may have the property of reducing  $T_G$ .

It is important that the stressed layer 2 be covered with the glassy layer 4 before germanium contained in the stressed layer 2 is able to diffuse into the atmosphere, and before the stressed layer 2 is contaminated significantly, and before the surface of the stressed layer 2 becomes reactive in an uncontrollable way. This last condition may occur when the whole undergoes heat treatment at high temperature, such as an RTA type annealing treatment or a sacrificial oxidization treatment.

In an advantageous embodiment of the glassy layer 4, the following steps are applied onto the stressed layer 2. With reference to Figure 1b, a semiconductor material layer 3 is grown on the stressed layer 2. Next, with reference to Figure 1c, a controlled treatment is applied to transform

at least a portion of the layer formed in the first step into a viscous material, by heating to a viscosity temperature, for example, to thereby form the glassy layer 4. Advantageously, the material selected for the layer 3 is Si so that the stress level of the stressed layer 2 will not be  
5 changed. The thickness of the layer 3 that is formed is typically between about 5 Å and about 5,000 Å, and more particularly may be between about 100 Å and about 1,000 Å.

For the same reasons explained above, crystal growing during the growth step of the layer 3 is preferably applied before diffusion of Ge.  
10 That is, shortly after the formation of the stressed layer 2 if the temperature for forming the stressed layer 2 is maintained, or a rise in temperature subsequent to a fall in temperature to room temperature having been caused immediately after forming the stressed layer 2.

The preferred method for growing layer 3 is *in situ* growth directly in  
15 continuation of the growth of the stressed layer 2. The growth technique used may be an epitaxy LPD, CVD or MBE technique. The glassy layer 4 may be made by heat treatment under an atmosphere with a predetermined composition.

Thus, a Si layer 3 may undergo a controlled heat oxidation  
20 treatment in order to transform this layer 3 into a SiO<sub>2</sub> glassy layer 4. During the latter step, it is important to accurately control the parameters of the oxidation treatment (such as temperature, duration, oxygen concentration, the amounts of other gases in the oxidizing atmosphere, etc.) in order to control the oxide thickness and to stop oxidation in the  
25 vicinity of the interface between both layers 2 and 3. For such thermal oxidation, a dry oxygen or steam atmosphere will preferably be used at a pressure equal to or larger than 1 atm. Preferably, the oxidation duration will then be varied in order to control the oxidation of layer 3. However, this control may be made by varying one or several other  
30 parameters, either in combination or not, with the time parameter. If

necessary, reference may be made to U.S. Patent No. 6,352,942 for more details concerning an embodiment of such a SiO<sub>2</sub> glassy layer 4 on a SiGe layer.

According to a second embodiment of the glassy layer 4, and as a replacement for the growth and controlled treatment steps illustrated by Figures 1b and 1c, respectively, a deposition of atomic species may be applied by means for depositing atomic species on the stressed layer 2. In a first case, atomic species consisting of the glassy material will be deposited directly. Thus, for example, SiO<sub>2</sub> molecules may be deposited in order to form the SiO<sub>2</sub> glassy layer 4. In this second case, the following operations will be applied:

- deposition of amorphous Si atomic species to form an amorphous Si layer; and then:
- thermal oxidization of this amorphous Si layer to thereby form an SiO<sub>2</sub> glassy layer 4.

Whichever one of these deposition cases is selected, the deposition of the atomic species should be made before diffusion of Ge, and before contamination and uncontrolled surface reactivation of the stressed layer 2. Uncontrolled surface reactivation may occur if the stressed layer 2 remains at a high temperature.

Figures 1d, 1e and 1f illustrate steps for removing the stressed layer 2 and the glassy layer 4 from the donor substrate 1 in order to transfer them onto a receiving substrate 7. For this purpose, the method applies a technique consisting of two successive main steps:

- bonding the receiving substrate 7 to the glassy layer 4; and
- removing a portion of the donor substrate 1.

Figure 1i shows application of the bonding. But before bonding, an optional step for forming a bonding layer on at least one of the two surfaces to be bonded may be applied, this bonding layer having binding properties at room temperature or at higher temperatures. Thus, for

example, forming a  $\text{SiO}_2$  layer may improve the quality of the bond, notably if the other surface to be bonded is  $\text{SiO}_2$  or Si. This  $\text{SiO}_2$  bonding layer is then advantageously made by depositing  $\text{SiO}_2$  atomic species, or, if the surface of the latter is in Si, by thermal oxidization of the surface to be bonded.

The surfaces to be bonded may be advantageously prepared before bonding in order to make the surfaces as smooth and as clean as possible. Suitable chemical treatments for cleaning the surfaces to be bonded may be applied, such as weak chemical etchings, an RCA treatment, ozone baths, rinses, etc. Mechanical or mechanical/chemical treatments may also be applied such as polishing, abrasion, CMP (Chemical Mechanical Planarization) or atomic species bombardment.

The bonding operation as such is carried out by bringing the surfaces to be bonded into contact with one another. Bonding linkages are preferably of a molecular nature wherein the hydrophilic properties of the surfaces to be bonded are utilized. In order to impart or enhance the hydrophilic properties of these surfaces, both structures may be dipped in baths or otherwise treated before bonding, for example, they could be rinsed with deionized water.

An annealing step may further be applied to reinforce the bonding linkages, for example, by changing the nature of the bonding linkages, such as covalent linkages or other linkages. Thus, if the glassy layer 4 is made of  $\text{SiO}_2$ , annealing may enhance the bonding linkages, especially if a  $\text{SiO}_2$  bonding layer has been formed prior to bonding to the receiving substrate 7.

If further details regarding bonding techniques are needed, reference may be made to the document entitled "Semiconductor Wafer Bonding" (Science and technology, Interscience Technology) by Q.Y.Tong, U.Gösele and Wiley.

Once the layers are bonded, material may be removed by separating a portion of the donor substrate 1 at a weakened area 6 present in the donor substrate 1 by supplying energy. With reference to Figures 1d and 1e, the weakened area 6 is an area substantially parallel to the bonding surface, and it has a linkage weakness between the lower portion 1a of the donor substrate 1 and the upper portion 1b. The weakness area may be broken to separate the upper portion 1B from the lower portion 1A when thermal or mechanical energy is supplied. According to a first embodiment of the weakened zone or area 6, a technique called SMART-CUT® is applied that first includes implanting an atomic species into the donor substrate 1, at the weakened area 6. The implanted species may be hydrogen, helium, a mixture of both of these species or other lightweight species. The implantation preferably occurs just before bonding. The implantation energy is selected so that the species that is implanted travels through the surface of the glassy layer 4, across the thickness of the glassy layer 4, across the thickness of the stressed layer 2, and to a predetermined depth or thickness of the upper portion 1b of the receiving substrate 1. Implantation into the donor substrate 1 is preferably sufficiently deep so that the stressed layer 2 does not suffer any damage during the detaching step from the donor substrate. The implant depth in the donor substrate is thus typically about 1,000 .

The weakness of the linkages in the weakened area 6 mainly depends upon the selection of the dosage of the implanted species. The dosage is typically between about  $10^{16} \text{ cm}^{-2}$  and  $10^{17} \text{ cm}^{-2}$  and more specifically between about  $2 \cdot 10^{16} \text{ cm}^{-2}$  and about  $7 \cdot 10^{16} \text{ cm}^{-2}$ . Detachment of the weakened area 6 is then usually carried out by supplying mechanical and/or thermal energy. For more details concerning the SMART-CUT® method, reference can be made to the document

entitled "Silicon-On-Insulator Technology: Materials to VLSI, 2<sup>nd</sup> edition" by J.-P. Colinge, edited by Kluwer Academic Publishers, pp. 50 and 51.

According to a second embodiment, a technique that is described in U.S. Patent No. 6,100,166 may be applied to form the weakened area  
5 6. The weakened layer 6 is made before forming the stressed layer 2 and during the formation of the donor substrate 1. The weakened layer may be formed by:

- forming a porous layer on a Si backing substrate 1A;
- growing a Si layer 1B on the porous layer.

10 The backing substrate 1A, porous layer and Si layer 1B form the donor substrate 1, and the porous layer forms the weakened area 6 of the donor substrate 1. Detachment can occur by supplying thermal and/or mechanical energy at the porous weakened area 6, to detach the backing substrate 1A from the layer 1B.

15 The techniques for removing material at a weakened area 6, achieved according to one of the two non-limiting embodiments above, enables a rapid removal of a large portion of the donor substrate 1. Such techniques also permit reuse of the removed portion 1A of the donor substrate 1, for example, to form another donor substrate that could be  
20 used, for example, according to the present method. Thus, a stressed layer 2 may be reformed on the portion 1A that has been removed, and another optional portion of a donor substrate and/or other layers may also be applied, preferably after polishing the surface of the portion 1A.

With reference to Figure 1f, after separating the remaining portion  
25 1B from the removed portion 1A of the donor substrate 1, a finishing step can be applied to enable the remaining portion 1B to be removed. Finishing techniques such as polishing, abrasion, CMP planarization, RTA thermal annealing, sacrificial oxidization, chemical etching, can be taken alone or in combination, and may be applied for removing the portion 1B  
30 and for perfecting stacking (strengthening the bonding interface, removal

of bumps, curing defects, etc.). Advantageously, at least at the end of finishing a step, the removal includes selective chemical etching, either combined or not with mechanical means. Thus, solutions based on KOH, NH<sub>4</sub>OH (ammonium hydroxide), TMAH, EDP or HNO<sub>3</sub>, or solutions  
5 presently investigated which combine agents such as HNO<sub>3</sub>, HNO<sub>2</sub>, H<sub>2</sub>O<sub>2</sub>, HF, H<sub>2</sub>SO<sub>4</sub>, H<sub>2</sub>SO<sub>2</sub>, CH<sub>3</sub>COOH, H<sub>2</sub>O<sub>2</sub> and H<sub>2</sub>O (as explained in document WO 99/53539, page 9) may advantageously be used for selectively etching the Si portion 1B relative to the stressed Si<sub>1-x</sub>Ge<sub>x</sub> layer 2.

After the bonding step, another technique could be applied to  
10 remove a portion of the donor substrate 1 that does not use a weakened area. This technique consists of applying chemical and/or mechanical/chemical etching. For example, optional selective etchings for the material(s) to be removed from the donor substrate 1 may be applied according to an etch-back type method. This technique consists of  
15 etching the donor substrate 1 from the back, i.e. from the free face of the donor substrate 1. Wet etchings may be applied that apply etching solutions suitable for the materials to be removed. Dry etchings may also be applied for removing material, such as plasma or spray etchings. Etching(s) may further only be chemical or electrochemical or  
20 photochemical. Etching(s) may be preceded or followed by mechanical abrasion of the donor substrate 1, such as grinding, polishing, mechanical etching or spraying of atomic species. The etching(s) may be accompanied by mechanical abrasion, such as an optional polishing step combined with the action of mechanical abrasives using, for example, a  
25 CMP method.

All the aforementioned techniques for removing material from the donor substrate 1 are provided by way of example, but do not limit the present method. The removal method extends to all types of techniques capable of removing material from the donor substrate 1, in accordance  
30 with the present method.



With reference to Figure 1f, a portion 1B of the donor substrate 1 is preserved after removal. The stressed layer 2 is buried and thus protected from the external atmosphere. Regardless of which technique is used for removing material, selected from the techniques already discussed or from other known techniques, a surface finishing step for the remaining portion 1B of the donor substrate 1 may be advantageously applied. The finishing step may include selective chemical etching, or CMP polishing, or heat treatment, or bombardment with atomic species or any other smoothing technique.

Thus, after applying a step for removing material that included using a SMART-CUT® type technique, a smoothing treatment can be used, such as one of the following treatments:

- polishing in order to obtain a thickness of between about 200 Å to about 800 Å;
- Ar/H<sub>2</sub> RTA fast annealing followed by polishing in order to obtain a thickness of between about 200 Å to about 800 Å;
- a single fast RTA annealing; or
- Ar/H<sub>2</sub> oven annealing.

These finishing treatments are particularly suitable for application to a Si surface (of the remaining portion 1B of the donor substrate 1). It is noted that if the SiGe stressed layer 2 had been exposed, it would have been difficult to apply such techniques without deterioration of the stressed layer 2, as these techniques do not work well for SiGe. Thus, it is an advantage of the above described method that the surface of the Si surface layer 1B can be efficiently smoothed after detachment.

With reference to Figure 1f, after removal of the material, a structure is obtained that includes the receiving substrate 7, the glassy layer 4, the stressed layer 2 and a Si surface layer 1B (which represents the remaining portion of the donor substrate 1). The stressed layer 2 is

thus substantially protected from the outside environment by the overlying surface layer 1B and the underlying glassy layer 4.

According to an alternative method, the surface layer 1B is preserved as is. However, with reference to Figure 1g, a second glassy layer 8 is formed at the surface of the structure consisting of a viscous material using a treatment having a second viscosity temperature to form it. The selected material for the second glassy layer 8 may, for example, be one of the following materials:  $\text{SiO}_2$ , BPSG,  $\text{SiO}_x\text{N}_y$ . This second glassy layer 8 is preferably formed by transforming the surface layer 1B into a glassy layer, by means of a suitable controlled treatment. Thus, the second glassy layer 8 may be created by using a heat treatment under an atmosphere having a predetermined composition. Thus, the Si surface layer 1B may undergo a controlled thermal oxidization treatment in order to transform this surface layer into a  $\text{SiO}_2$  glassy layer 8.

During the latter step, it is important to accurately control the various parameters of the oxidizing treatment (such as the temperature, the duration, the oxygen concentration, the other gases in the oxidizing atmosphere, etc.) in order to control the thickness of the oxide layer that is formed, and to stop oxidization in the vicinity of the interface between the layers 2 and 1B. A dry oxygen or steam atmosphere will preferably be used for such thermal oxidization, at a pressure equal to or larger than 1 atmosphere (atm), at a temperature between about  $500^\circ\text{C}$  and about  $1,050^\circ\text{C}$ . The duration of oxidization will preferably be varied so as to control the oxidization of the surface layer 8. However, control may also be accomplished by varying one or several of the other parameters, either combined with or separate from the time parameter.

Referring to Figure 1g, heat treatment is applied at a temperature close to or higher than the viscosity temperature. The main purpose of the heat treatment is to relax the stresses in the stressed layer 2. Heat treatment at a temperature higher than or around the viscosity

temperature  $T_G$  of the glassy layer 4 will cause the surface layer to become viscous, which will allow the stressed layer to relax at its interface with the glassy layer 4, resulting in decompression of at least part of its internal stresses. Thus, if the glassy layer 4 is an  $\text{SiO}_2$  layer created by thermal oxidization, heat treatment at a minimum of about  $1,050^\circ\text{C}$ , and preferably at about a minimum of  $1,200^\circ\text{C}$  for a predetermined duration, will cause relaxation or pseudo-relaxation of the stressed layer 2. The heat treatment typically lasts between a few seconds and several hours.

The relaxation of the stressed layer 2 is achieved without the stressed layer 2 coming into with the outside world, unlike when conventional methods are used, by preventing diffusion of Ge. The stressed layer 2 therefore becomes a relaxed layer 2'.

Other effects of the heat treatment on the structure may be sought, in addition to the relaxation of the stressed layer 2. For example, another reason for using heat treatment may be to anneal to strengthen the bond between the receiving substrate 7 and the glassy layer 4. In fact, because the temperature selected for heat treatment is higher than or around the viscosity temperature of the glassy layer 4, the latter having temporarily become viscous, strong adhesion linkages may be generated with the receiving substrate 7. Thus, again taking the example of bonding between the  $\text{SiO}_2$  glassy layer 4 and the receiving substrate on which a  $\text{SiO}_2$  bonding layer has been applied, the viscosities of both of the layers in contact will generate particularly strong covalent linkages.

Another purpose for applying heat treatment is to form the second  $\text{SiO}_2$  glassy layer 8 by thermal oxidization. It may be desirable to form this glassy layer 8 during or immediately after using heat treatment to relax the stressed layer 2, by simultaneously injecting oxygen into an oven, or else by following that heat treatment with another heat cycle.

As shown in Fig. 1g, a structure 20 is obtained that includes the glassy layer 8, a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer 2', a glassy layer 4, and a receiving

substrate 7. The relaxed  $\text{Si}_{1-x}\text{Ge}_x$  of layer 2' is thereby protected from the outside by the adjacent glassy layers 4 and 8. In order to expose the relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer 2', it is then sufficient to remove the glassy layer 8, for example, by means of a suitable chemical treatment. Thus, if the  
 5 glassy layer 8 is made of  $\text{SiO}_2$ , the structure 20 will advantageously be treated with hydrofluoric acid HF in order to remove  $\text{SiO}_2$  from the glassy layer 8.

With reference to Figure 1h, a structure 30 is formed including a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer 2', a glassy layer 4, and a receiving substrate 7.  
 10 This structure 30 is a SGOI structure (Silicon Germanium On Insulator) if the glassy layer 4 is electrically insulating, such as for example a  $\text{SiO}_2$  glassy layer 4. The relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer 2' of this structure advantageously has a surface with a surface roughness compatible with growth of another crystalline material. A surface treatment such as a light  
 15 polishing, suitable for  $\text{Si}_{1-x}\text{Ge}_x$ , may optionally be applied in order to improve surface properties.

With reference to Figure 1i, an optional step of the present method includes growing a Si layer 11 on the relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer 2'. The Si layer is applied with a thickness substantially less than the stress critical  
 20 thickness of the material of which it consists, and it is therefore stressed by the relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer 2'. Thus, a structure consisting of a stressed Si layer, a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  2' layer, a glassy layer 4, and a receiving substrate 7 is obtained. This structure 40 is a Si/SGOI structure if the glassy layer 4 is electrically insulating, such as for example a  $\text{SiO}_2$  glassy  
 25 layer 4.

Alternatives of the present method are presented with reference to Figures 2a-2i, Figures 3a-3i, and Figures 4a-4i.

With reference to Figures 2a-2i, and more particularly to Figure 2g, the method is generally the same as that described with reference to  
 30 Figures 1a-1i, except for the step for transforming the surface layer 1B

into a second glassy layer 8. In this case, a different method is applied so that only a portion of the surface layer 1B is transformed. Thus, there exists a remainder or intermediate layer 9 of the Si surface layer 1B between the second glassy layer 8 and the stressed layer 2. With  
5 reference to Figure 2h, this intermediate layer 9 is preserved after heat treatment for relaxing the stressed layer 2. The intermediate layer 9 is advantageously preserved with a thickness less than the stress critical thickness so that it is stressed subsequently by the relaxed layer 2'.

With reference to Figure 2i, growing a Si layer may be resumed on  
10 the intermediate layer 9 in order to form a stressed Si layer 11 substantially identical to that of Figure 2i. A smoothening step could be applied to the growth surface by means of one of the techniques already discussed before growth of silicon, in order to improve the quality of the crystal growth.

15 If heat treatment is applied to relax the stresses of the stressed layer 2 at a higher than standard temperature and for longer than a standard duration, then the Ge diffuses into Si and the Ge contained in the stressed layer 2 may diffuse into the intermediate layer 9. Thus, it is preferable to apply the relaxation of the stressed SiGe layer 2 before  
20 resuming epitaxial growth of the stressed Si layer 11. However, in certain other cases, this diffusion effect may be sought if it is suitably controlled. Thus, diffusion may be controlled in such a way that the Ge species are uniformly distributed throughout both layers 2 and 9, forming a unique  $\text{Si}_{1-x}\text{Ge}_x$  layer with a substantially uniform Ge concentration. A discussion  
25 of this latter point can be found in U.S. Patent No. 5,461,243 at column 3, lines 48-58.

Referring to Figures 3a-3i, and more particularly to Figure 3c, the method illustrated is generally the same as the one described with reference to Figures 1a-1i, except for the step of transforming a layer 3  
30 into a glassy layer 4 which is applied so that only a portion of the layer 3 is

transformed. Thus, a portion of the Si layer 3 remains inserted between the glassy layer 4 and the stressed layer 2, forming an inserted layer 5. This inserted layer 5 is created to have a thickness of about 10 nm, in any case much less than that of the stressed layer 2. During heat treatment  
 5 for relaxing the stress of the stressed layer 2, the latter will want to reduce its internal elastic stress energy by utilizing the viscosity properties of the glassy layer 4 which has become viscous. Further, because the inserted layer 5 has a small thickness relatively to the overlying stressed layer 2, the stressed layer 2 will impose its relaxation requirement on the inserted  
 10 layer 5. The stressed layer 2 thereby forces the inserted layer 5 to be at least partially under stress. The stressed layer 2 then becomes an at least partially relaxed layer 2'. The relaxed inserted layer 5 then becomes a stressed inserted layer 8'. A discussion of the latter point can be found in U.S. Patent No. 5,461,243 at column 3, lines 28-42.

15 With reference to Figure 3h, the stressed inserted layer 5' is preserved after the heat treatment for relaxing the stressed layer 2. The structure that is formed consists of a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer, a stress Si layer, a glassy layer 4, and a receiving substrate 7. This structure 30 is a SG/SOI structure if the glassy layer 4 is electrically insulating, such as, for  
 20 example, a  $\text{SiO}_2$  glassy layer 4. It is then possible to optionally remove, for example by selective chemical etching based on  $\text{HF}:\text{H}_2\text{O}_2:\text{CH}_3\text{COOH}$  (selectivity of about 1:1,000), the relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer 2', in order to finally obtain a structure consisting of a stressed Si layer, a glassy layer 4, and a receiving substrate 7. This structure is a stressed SOI structure if  
 25 the glassy layer 4 is electrically insulating, such as, for example, a  $\text{SiO}_2$  glassy layer 4.

Instead of applying chemical etching, it is possible to resume growth of a Si layer on the relaxed layer 2' as shown in Figure 3i, so as to form a stressed Si layer 11. The resulting structure 40 consists of a  
 30 stressed Si layer, a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer, a stressed Si layer, a glassy

layer 4, and a receiving substrate 7. This structure 40 is a Si/SG/SOI structure, if the glassy layer 4 is electrically insulating, such as, for example, a SiO<sub>2</sub> glassy layer 4. In a particular scenario, if heat treatment for relaxing the stresses of the stressed layer 2 is carried out at a temperature that is higher than a standard temperature and for longer than a standard duration, such that Ge diffuses into Si, the Ge contained in the stressed layer 2 may diffuse into the stressed inserted layer 5'. Thus, it is preferable to apply the relaxation of the stressed SiGe layer 2 before resuming epitaxy of the stressed Si layer 11. But this diffusion effect may be desirable in certain other cases, and the parameters may be suitably controlled to obtain this result. Thus, diffusion may be controlled in such a way that the Ge species are distributed uniformly throughout both layers 2 and 5 to form a unique Si<sub>1-x</sub>Ge<sub>x</sub> layer with a substantially uniform Ge concentration. A discussion of the latter point can be found in U.S. Patent No. 5,461,243, at column 3, lines 48-58.

With reference to Figures 4a-4i, and more particularly to Figures 4c and 4g, a method is illustrated that generally is the same as the one described with reference to Figures 1a-1i, except that:

- Only part of the layer 3 is transformed into a glassy layer 4;
- The surface layer 1B is not transformed into a second glassy layer 8.

In fact, this method includes a step identical to the one described with reference to Figure 3c, forming an inserted layer 5 (see Figure 3c), and a step identical to the one described with reference to Figure 2g, forming an intermediate layer 9 (see Figure 2g). The means for forming both of these layers 5 and 9, as well as the possibilities for developing their structure and their effect on the final structure, are therefore substantially the same as those described with reference to Figures 2a-2i and to Figures 3a-3i.

With reference to Figures 5a-5h, and more particularly to Figures 5b and 5d, the method is generally the same as the one described above with reference to Figures 1a-1i, except that:

- with reference to step 5b, the epitaxial Si layer 3 on the stressed layer 2 is a very thin layer, the thickness of which is much less than that of the stressed layer 2, typically from about 100 to 300 Å;
- with reference to Figure 5d, the glassy layer 4 is formed on the receiving substrate 7.

The Si layer 3 will thus enable the overlying SiGe stressed layer 2 to be protected from Ge diffusion, external contamination and uncontrolled potential reactivation of its surface. A suitable surface finishing method can be applied to the Si, whereas such suitable methods do not exist for SiGe. These finishing techniques (already detailed above) may provide good bonding with the receiving substrate 7.

With reference to Figure 5d, according to a first embodiment, the glassy layer 4 is formed before bonding onto the receiving substrate 7. The material forming the glassy layer 4 is such that it becomes viscous at a viscosity temperature  $T_G$ . Advantageously, the material of the glassy layer 4 is one of the following materials: BPSG, SiO<sub>2</sub>, SiON. This first embodiment for forming the glassy layer 4 on the receiving substrate is similar to the first embodiment for forming the glassy layer 4 on the stressed layer 2 as described above with reference to Figure 1c. Thus, for example, oxidization of the Si surface of the receiving substrate 7 may form a SiO<sub>2</sub> glassy layer 4. It is important that the formation of the glassy layer 4 and the bonding of the glassy layer 4 with the stressed layer 2 be completed before Ge diffusion, contamination and uncontrolled reactivation of the surface of the stressed layer 2, especially if the stressed layer 2 remains at a high temperature.

According to a second embodiment for forming the glassy layer 4 on the receiving substrate, deposition of atomic species is applied by



means for depositing atomic species on the receiving substrate 7. In a first case, the atomic species consisting of glassy material such as  $\text{SiO}_2$  will be directly deposited. In a second case, the following operations will be applied:

- 5           •       deposition of amorphous Si atomic species in order to form an amorphous Si layer, and then:
- thermal oxidization of the amorphous Si layer to thereby form a  $\text{SiO}_2$  glassy layer 4.

10           Whichever deposition case is selected, deposition of the atomic species should be achieved before Ge diffusion, contamination and uncontrolled reactivation of the surface of the stressed layer 2, and especially if the stressed layer 2 remains at a high temperature.

15           With reference to Figures 5e, 5f, 5g and 5h, the same conditions and the same configurations as those discussed above with reference to Figures 3f, 3f, 3h and 3i apply, whereby the referenced layer 5 becomes the referenced layer 3 in the present method. In particular, during the heat treatment for relaxation the stressed layer 2 becomes at least a partially relaxed layer 2', and the inserted layer 3 then becomes a stressed inserted layer 3'.

20           With reference to Figure 5g, the formed structure consists of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , a stressed Si layer, a glassy layer 4, and a receiving substrate 7. This structure 30 is a SG/SOI structure, if the glassy layer 4 is electrically insulating, such as for example a  $\text{SiO}_2$  glassy layer 4. The relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer 2' may then be optionally removed, for example by  
 25           selective chemical etching based on  $\text{HF}:\text{H}_2\text{O}_2:\text{CH}_3\text{COOH}$  (selectivity of about 1:1,000) in order to finally have a structure consisting of a stressed Si layer, a glassy layer 4, and a receiving substrate 7. This structure is a stressed SOI structure, if the glassy layer 4 is electrically insulating, such as for example a  $\text{SiO}_2$  glassy layer 4.

Instead of applying chemical etching, it is possible to grow a Si layer, with reference to Figure 5h, by resuming growth on the relaxed layer 2' in order to form a stressed Si layer 11, substantially identical to that shown in Figure 5h. The structure 40 consists of a stressed Si layer, a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer, a stressed Si layer, a glassy layer 4, and a receiving substrate 7. This structure 40 is a Si/SG/SOI structure, if the glassy layer 4 is electrically insulating, such as for example a  $\text{SiO}_2$  glassy layer 4.

If the heat treatment for relaxing the stresses of the stressed layer 2 is carried out at a higher than standard temperature and longer than a standard duration for which Ge diffuses into Si, then the Ge contained in the stressed layer 2 may diffuse into the stressed inserted layer 3'. This is why it is preferable to apply relaxation of the stressed SiGe layer 2 before resuming epitaxial growth of the stressed Si layer 11. However, in certain cases, this diffusion effect, if it is suitably controlled, may be desired.

Thus, diffusion may be controlled in such a way that the Ge species are uniformly distributed throughout both layers 2 and 5, forming a unique  $\text{Si}_{1-x}\text{Ge}_x$  layer with a substantially uniform Ge concentration. A discussion of this point can be found in U.S. Patent No. 5,461,243 at column 3, lines 48-58.

With reference to Figures 6a-6h, and more particularly to Figure 6f, the method is generally the same as the one described with reference to Figures 5a-5h, except for the step for transforming the surface layer 1B into a second glassy layer 8, which is applied to transform only a portion of the surface layer 1B. Thus, a portion of the Si surface layer 1B remains inserted between the second glassy layer 8 and the stressed layer 2, forming an intermediate layer 9. With reference to Figure 6g, this intermediate layer 9 is preserved after the heat treatment for relaxing the stressed layer 2. Advantageously, this intermediate layer 9 has a

thickness less than the stress critical thickness, so that it is stressed subsequently by the relaxed layer 2'.

With reference to Figure 6h, it is possible to resume growth of a Si layer on the intermediate layer 9 so as to form a stressed Si layer 11, substantially identical with that of Figure 5h. A smoothing step for the growth surface by means of one of the techniques already discussed above may be applied prior to growing silicon, in order to enhance the quality of the crystal growth to be applied.

If the heat treatment for relaxing the stresses of the stressed layer 2 is carried out at a temperature and for a duration higher than a standard temperature and longer than a standard duration, wherein Ge diffuses into Si, then Ge contained in the stressed layer 2 may diffuse into the intermediate layer 9 or into the inserted layer 3. This is why it is preferable to apply the relaxation of the stressed SiGe layer 2 before resuming epitaxial growth of the stressed Si layer 11. However, in certain other cases, this diffusion effect, if it is suitably controlled, may be desired. Thus, diffusion may be controlled so that the Ge species are uniformly distributed throughout both layers 2, 3 and 9, forming a unique  $\text{Si}_{1-x}\text{Ge}_x$  layer with a substantially uniform Ge concentration. A discussion of this point can be found in U.S. Patent No. 5,461,243 at column 3, lines 48-58.

Steps for making components can be integrated according to any of the six methods described above, or by equivalents thereof. Thus, preparation steps for making components may be applied during the method at the stressed SiGe layer 2 of the structure with reference to Figures 1g, 2g, 3g, 4g, 5f or 6f, at the relaxed or pseudo-relaxed SiGe layer 2' of the SGOI structure with reference to Figures 1h, 2h, 3h, 4h, 5g or 6g, or in the stressed Si layer 11 of the Si/SGOI structure with reference to Figures 1i, 2i, 3i, 4i, 5h or 6h. Preferably, these preparation steps will be achieved with the glassy layer 8 always present in the structure, the latter protecting the underlying layers, and especially the

stressed layer 2 or the relaxed layer 2', both in SiGe. For example, local treatments may be undertaken for etching patterns in the layers through the glassy layer 8, for example by lithography, photolithography, reactive ion etching, or any other etching technique with pattern masking.

5           In a particular case, patterns such as islands can be etched into the SiGe stressed layer 2 in order to contribute to proper relaxation of the stressed layer 2 during the subsequent application of the relaxation heat treatment.

10           One or several steps for making components, such as transistors, in the stressed Si layer 11 (or in the relaxed SiGe layer 2' if the latter is not covered with a stressed Si layer 11) may be applied, preferably at a temperature less than  $T_G$  (so as not to change the stress ratio of the relaxed layer 2' and the stressed layer 11).

15           In a particular method according to the invention, steps for making the components are applied during or in continuity with the heat treatment for relaxing the stressed SiGe layer 2.

          In a particular method according to the invention, the step for epitaxial growth of the stressed Si layer is applied during or in continuity with the steps for making the components.

20           The techniques described in the invention are provided by way of example, but are by no means limited, because the invention may extend to all types of techniques that could apply a method according to the invention.

25           One or any epitaxial growth processes may be applied onto the final structure (structure 30 or 40 taken with reference to Figure 1h, 1i, 2h, 2i, 3h, 3i, 4h, 4i, 5g, 5h, 6g, 6h), such as epitaxial growth of a SiGe or SiGeC layer, or of a stressed Si or SiC layer, or successive epitaxial growths of SiGe or SiGeC layers and of alternately stressed Si or SiC layers in order to form a multilayer structure.

Upon completion of the final structure, finishing treatments may optionally be applied, including an annealing step, for example.

The present invention is also not limited to a SiGe stressed layer 2, but also extends to forming the stressed layer 2 in other types of materials of the III-V or II-VI type, or other semiconductor materials.

In the semiconductor layers discussed in this document, other constituents may be added thereto, such as carbon with a carbon concentration in the relevant layer substantially less than or equal to 50% or, more particularly with a concentration less than or equal to 5%.

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